Fermi National Accelerator Laboratory

The Magnetic Design and Field Measurement of Fermilab Collider Detectors: CDF and D0*

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ABSTRACT

General magnetic characteristics of the CDF and D0 hadron collider detectors at Fermilab are described. The method and equipment for the field measurement for both detectors are described, and their field measurement data are presented. The magnetic field distribution inside the CDF solenoid magnet was measured extensively only at the boundaries, and the field values inside the volume were reconstructed. The effects due to the joints and the return conductor were measured and are discussed. The flux distribution inside the yokes and the fringing field of the D0 toroids were calculated and compared with measured data. A proposal to generate dipole magnetic field inside the D0 toroidal magnet is discussed.

INTRODUCTION

At Fermilab, there are two major hadron collider detectors: CDF (the Collider Detector at Fermilab) and D0; both are general-purpose collider detectors and weigh more than 4000 tons each.

The CDF is located in the B0 straight section of the Energy Doubler ring. It is composed of the central detector, the forward and backward detectors, and others.[1] This detector was built with the collaboration of U.S., Japan, and Italy and has been in operation since 1986 for high energy physics experiments.

The D0 detector is under construction at the D0 straight section, and is expected to be in full operation early in 1991.[2] The D0 detector has three major and two small toroidal magnets. The major toroids were completed and excited without two small toroids early this year (1989).

CDF

The central part of the CDF detector is constructed with a structurally complicated yoke, and excited with a cylindrical thin-walled superconducting solenoidal coil.

Design of central magnet structure

The central detector weighs about 2,200 metric tons and is shown in Fig. 1 together with its field mapping device. The magnetic circuit of this detector is composed of a 1.5 Tesla superconducting solenoid, the 2 in. thick iron plates used as pole pieces and also as part of the return yoke, and 8 in. thick iron slabs used in the end wall and return legs. The central hadron calorimeter is made of 1 in. thick iron plates which are partially magnetized unintentionally due to the proximity of the magnetic circuit.

TRIM calculation

A two-dimensional magnetostatic program, TRIM, was used to calculate the magnetic field distribution of the CDF magnet. Its accompanying program, FORGE, was applied to estimate forces on the yoke, coil, and calorimeters.[3] The magnetic structure of the CDF detector, which was used for
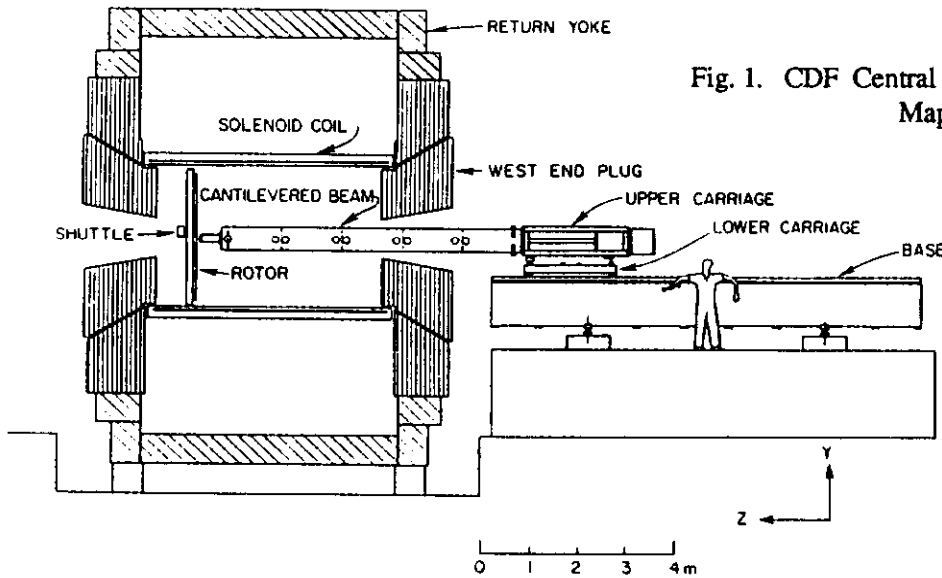
Fig. 1. CDF Central Magnet Structure and Field Mapping Device

the field calculation, is shown in Fig. 2. For reasons of simplicity and symmetry, its geometry was assumed completely axi-symmetric and only a quadrant was used. The resulting magnetic field and flux distribution is shown in Fig. 3.

At the excitation of 1.5 Tesla, each plug is pulled inward by a force of 540 metric tons. Therefore, an extensive study on the magnetic field distribution and its resulting magnetic force distribution was required. The stress and deflection of these components due to the magnetic force, as well as those due to gravitational force, were calculated using finite element analysis.[4]

Thin-walled superconducting solenoid

A thin-walled superconducting solenoid is used to magnetize the central magnet. This solenoid was designed by the collaboration of Fermilab, Tsukuba University, and Hitachi Ltd., and built at Hitachi Ltd.[5] This coil has been in operation since 1985, and it was run continuously for about a year from summer 1988 to spring 1989.

This solenoid has a 16-mm-thick outer aluminum bobbin, which works to restrain the coil conductors from moving and quenching. It also works as a one-turn secondary conductor with respect to the coil winding, when the coil quenches. Thus, the bobbin itself rapidly heats up uniformly and eventually heats the coil uniformly, leading to safe quenching, because it avoids dangerous local heating in the coil.

The superconductor is a monolithic conductor,

with the regular NbTi superconductor embedded in pure aluminum by the EFT method (extrusion with front tension), which was developed and manufactured at Hitachi Cable Ltd. The outside dimensions of the conductor are 3.89 mm x 20.0 mm. The ratio of NbTi/Cu/Al is 1/1/21.

The coil has 1164 turns and is made of 11 long conductors. Therefore, there are 10 joints along the length of the coil. The joints were made by welding pure aluminum of two adjacent turns completely around the circumference.

Automatic field mapping device for CDF

The general mechanical features of the mapping device are shown in Fig. 1. The major components are the base, the carriage, the long cantilevered beam, the rotor, and the shuttle. To eliminate eddy current effects, the beam, rotor, and shuttle are made of carbon-fiber composite. On the shuttle are mounted the sensing elements. The whole system is designed so that the sensing elements (search coils) can be placed with a positional accuracy of 0.75 mm in space coordinates and an angular accuracy of ± 1 mrad.[6]

A search coil system with three components is used to measure the magnetic field in three dimensions. The output voltages of the search coils are connected to individual integrators and the resultant voltages, which are proportional to the field changes, are sent to an ADC in a CAMAC system. To monitor the drift of the integrators DVM's with a micro-volt range were used.

Fig. 2. Magnetic Structure Used for Computer Calculation

Fig. 3. Magnetic Field and Flux Distribution in Central Magnet

The sensitivity of the field measurement could be varied by changing the integrator time constants. In the central region, the axial fields (Bz) were measured to a precision of 0.5 Gauss. In the end-plug regions, Bz was measured with errors on the order of 14 Gauss. The radial component of the field was measured with a sensitivity of 0.5 Gauss in the central region and 4 Gauss in the endplug regions. The azimuthal component of the field was measured everywhere with a sensitivity of 0.7 Gauss.

In the central uniform field region, an NMR probe was used to get precise absolute field values with an accuracy less than 1 Gauss. In the central re-

gion, the magnitude of the magnetic field is essentially the same as the z component of the field, as the radial and azimuthal components are typically less than or on the order of 10^{-3} x Bz. During the measurement, a second NMR probe was mounted on the inside surface of the west end-plug and used to monitor the field at a fixed point for normalization purpose.

Data acquisition and manipulator motion control were handled by an IBM-PC interfaced to CAMAC via a Transiac Model 6002 crate controller. In addition, the Modulynx stepping motor controller was commanded by the PC through a CAMAC GPIB interface module. The IBM-PC was used only for the on-line data acquisition and system control. Raw data were transferred via an RS-232 serial link to a DEC VAX computer for further analysis and also for online graphical display of measurement data.

Field measurement data

For most of the measurements, the magnet was operated at its nominal current of 5000 amps corresponding to a field of 15 kG. In the inside volume of the solenoid most of the field measurement was done with the three-dimensional search coils and with a stationary NMR as a standard.

For complete field mapping, the field was measured on the boundary of a cylindrical surface and these data were then used to perform a fit based on Maxwell's equations. The fitting of the magnetic field data was performed using a procedure developed by Wind.[7] The fit coefficients were used to calculate values of the magnetic field inside the cylinder. These calculated values were then compared to measurements of the field within the cylindrical surface. The agreement was excellent. With this method the measurement time is reduced substantially because we have to measure only on the outer boundary surfaces.

The field distribution near the center of the magnet was scanned in detail with an NMR probe. The field distribution in the central region can be parameterized as follows:

$$B = 15083.86 - 7.46 \times 10^{-3} \times (z+25)^2 + 3.75 \times 10^{-3} \times r^2$$

where B is in Gauss and z are r are in cm. The B gives the magnitude of the field, but it is essentially equal to Bz. This shows the shifting of the mag-

netic center to the geometrical center by 25 cm, which may be due to the slight shifting of the coil, or slight non-uniform winding of the coil.

Non-uniformities in the field due to joints in the conductor and to the solenoid return lead were studied extensively. These joints cause local dips in the magnetic field strength near the joint. The effect of the joints is shown in Fig. 4, which was measured near the surface of the solenoid, at r=135 cm (14 cm away from the conductor) and on the axis. Similarly the return conductor, which runs perpendicularly to the winding conductors, causes local field disturbance near the surface of the solenoid.
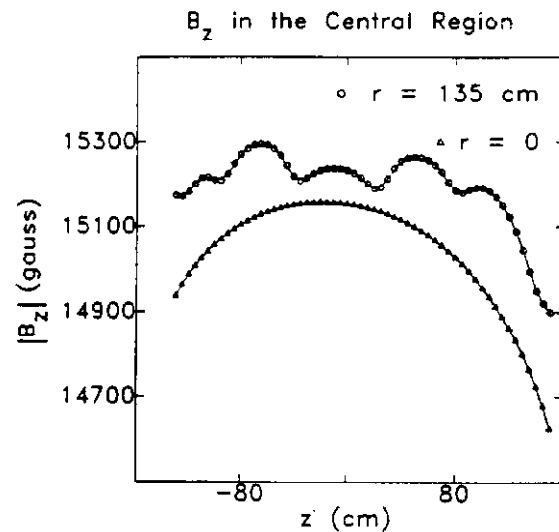

Fig. 4. Magnetic Field Distribution on Axis (r=0) and Near Coil (r=135cm)

D0 DETECTOR

A perspective view of the D0 detector is shown in Fig. 5. The overall dimensions of the D0 detector are 11.6 m wide, 12.9 m high, and 19.7 m long along the beam line. Its total weight is about 5000 metric tons. From the center, there is a set of the central tracking detectors, three uranium liquid argon calorimeters, and a set of toroidal magnets with proportional drift chambers.

Design of toroidal magnets

The muon detection system is designed to provide nearly complete coverage down to 5 degrees with momentum measurement through iron magnets. There are three large toroids: one central toroid (CF) and two end-wall toroids (EF's). In ad-

dition, there are two small toroids (SAMUS) being manufactured at Serpukhov Institute for High Energy Physics which will be mounted inside the opening of the EF's late this year. The thickness of the CF toroid is 108.6 cm and its total weight is 1973 metric tons. The thickness of each EF is 152.4 cm and each weighs 800 metric tons. Each SAMUS toroid weighs 32 metric tons. The magnetic flux distribution were calculated with the two dimensional program POISSON.[8]

The central toroid is made of three parts: one central fixed beam and two side-moving yokes. It is shown in Fig. 6, with a platform. It can be split apart during the installation of chambers. There is a 1/8th in. gap at the top and 3/32nd in. gaps at the both sides of the central beam. These gaps are filled with stainless steel plates and are provided to reduce the remnant field inside the yoke to make the separation easy.

Excitation of toroidal magnets

Three major toroids (CF and two EF's) are connected in series and excited together with the maximum current of 2500 amp. The power supply is provided with a solid state reversing switch to measure the magnetic flux density in the toroids. It takes about 10 minutes to go from positive maximum current to negative maximum current, because the coil current needs to drop below 2 amp to make sure all four SCR's are in the off state. The

SAMUS toroids will be excited with a separate power supply.

Magnetic flux distribution inside yoke

The total of 36 flux loops were used to measure the magnetic flux in the yokes of toroids. These loops are made of one-turn coils around the cross section of the yoke. By numerically integrating the output of these loops during toroid excitation, we can measure the total flux change through that loop. Absolute flux values are obtained by cycling the current from the positive maximum current to the negative maximum current and dividing the total flux change by two. The flux value in CF at zero current is about 1.7 kG and takes a long time to settle.

For data acquisition system, we used an existing Macintosh based system with a combination of a high accuracy scanner and a 6-1/2 digit DMM.[9] Due to the high accuracy but low speed mode of the system, we measured the output of each flux loop at a scanning rate of 8.3 sec/cycle. To correct its slow rate, each loop is provided with an R-C integrator at the end of an individual cable. With a 1 MΩ resistor and a 15 μF capacitor, its time constant is 15 sec.

The flux densities inside the CF and EF were measured 1.84 and 1.93 Tesla respectively at the straight part of the yokes. The flux density distribution diagonally across the corner is decreasing toward
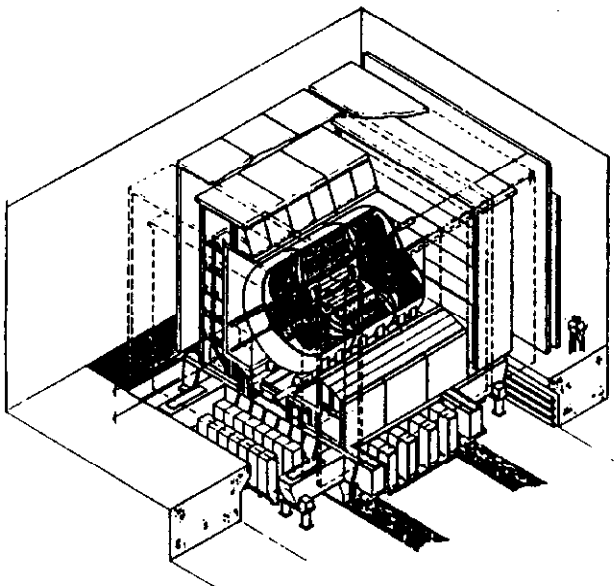
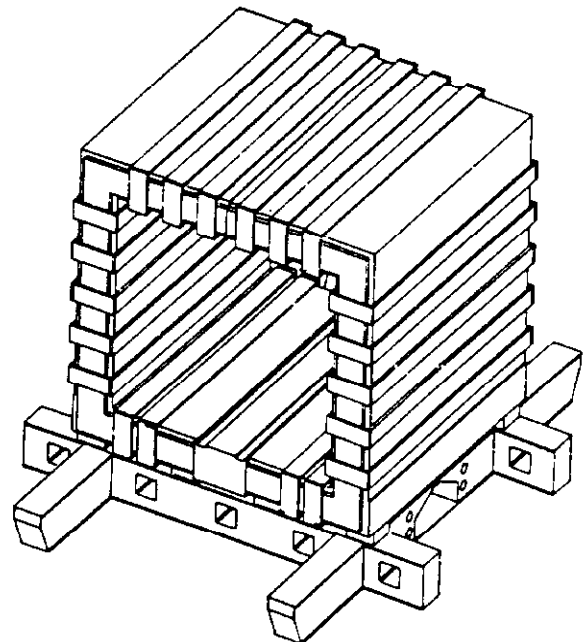

Fig. 5. Perspective View of the D0 Detector

Fig. 6. CF Toroid Mounted on Platform

the outside as expected. The remnant flux density inside CF with zero current is 1.68 kG, with corresponding values in EF's are changing radially from 4 to 1 kG.

Fringing field inside CF

The fringing field inside the CF was measured with a Hall probe Gaussmeter. The magnetic field value is about 6 Gauss at the center and linearly increasing about 120 Gauss at the surface of the bottom beam at z=140 cm. These data show a similar pattern like the 2-dimensional computer calculation but differ somewhat due to the 3-dimensional structure of CF and EF.

Dipole mode operation of CF

If needed in the future, the polarity of the unit coils of CF can be rearranged to generate dipole field of about 400 Gauss inside the volume of CF with the maximum current of 2500 amp.

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